

INTEGRATED MAGNETIC BEARING

This application claims the benefit of U.S. provisional application serial no. 60/248,464 filed on November 14, 2000, entitled "Integrated Magnetic Bearing".

Background of the Invention

1. Field of the Invention

The present invention relates generally to a rotational magnetic gimbal with an integral magnetic bearing. More particularly, the present invention relates to brushless DC motor technology that provides electromagnetic suspension, using a single electromagnetic actuator to perform both the bearing and rotary torque (motoring) functions.

2. Description of Related Art

Current rotational electric motors employ mechanical bearings in their ends or on the apparatus to which they are providing torque. Recent research in the area of combination motor-bearings has yielded working prototypes of both AC and DC machines. Although some AC machines can provide rotational positioning, more commonly these machines find application where a constant rotating speed is required in spite of load variations. The primary benefit is the potential for high power density and high-speed machines due to the smaller size (length/volume) of combination motor-bearings. Prototypes of AC type motor-bearings have matured to the point of finding applications in a bearingless blood pump and industrial roll.

Of more relevance to high accuracy pointing devices are combination motor-bearings of the DC type, which can provide relatively high torque and levitation forces at zero and low rotational speed. Furthermore, pure magnetic bearings are DC machines, for which a wealth of vibration isolation control algorithms and hardware has been developed. Figures 1A and 1B illustrate the present state-of-the-art in design of DC combination motor-bearings.

1 Figure 1A shows a brushless permanent magnet (PM) design where the commutation
2 action for motoring is performed using an angular position sensor and digital control logic (not
3 shown), and levitation is performed using radial position sensors and digital control logic (not
4 shown). This design uses PM's mounted on the surface of the rotor as field poles, and common
5 armature coils for motoring and suspension in the stator. Alternatively, the PM's can be
6 embedded in the rotor iron to achieve a stronger levitation force than the surface PM design.

7 Figure 1B shows a reluctance (stepper) motor design that uses a cylindrical, toothed rotor and
8 separate armature coils for motoring and levitation on the stator. The advantage of the stepper
9 motor design is that no angular position sensor is necessarily required. However, in very fine
10 pointing applications, such a sensor may be desirable to overcome torque ripple and cogging
11 common to stepper motor technology. Note that each of these designs is toothed, which creates
12 unwanted detent torque within the actuator and makes accurate pointing more difficult.

13 Evaluation of toothless actuators has been extensively considered by Airex Corporation to
14 eliminate cogging torque and increase peak torque and pointing accuracy for these applications.

15 While both of the designs shown in Figure 1A and Figure 1B offer control of only two
16 translational and one rotational degrees-of-freedom, the principle of operation can be extended to
17 three translational and two rotational degrees-of-freedom.

18 The most significant design issues for both AC and DC combination motor-bearings are
19 reducing the detrimental effects of magnetic flux cross coupling upon the motoring and bearing
20 control actions, and achieving target force and torque specifications. The main benefit of using
21 combination motor-bearings is reduced size and weight, which follows from common armature
22 coils and flux paths (iron) being used for generation of both motor torque and bearing force. This
23 design efficiency, however, creates potential for significant cross coupling effects that must be

1 carefully treated. The use of common flux paths for motoring and bearing functions must also be
2 carefully designed with regard to maximum torque and force generation capability. Since the
3 maximum flux in a path at any instant is limited by material saturation, the maximum achievable
4 force and torque trade-off against each other during operation. This tradeoff must be considered
5 during the design stage for successful application of the technology.

6 Summary of the Invention

7 The present invention provides a rotational magnetic gimbal with an integral magnetic
8 bearing. Brushless DC motor technology provides electromagnetic suspension, using a single
9 electromagnetic actuator to perform both the radial bearing and rotary torque (motoring)
10 functions.

11 An integrated motor and magnetic bearing consistent with the invention comprises a rotor
12 comprising a plurality of permanent magnets and a stator comprising a plurality of independently
13 controlled coil segments (or sets) magnetically coupled to the permanent magnets, the coil
14 segments comprising a plurality of coil phases. An integrated motor and magnetic bearing may
15 further comprise a first and second radial position sensors, the first radial position sensor
16 disposed in or adjacent to a clearance gap between the rotor and the stator for sensing the
17 position of the rotor with respect to the stator along a first axis, and a second radial position
18 sensor disposed in or adjacent to the clearance gap between the rotor and the stator for sensing
19 the position of the rotor with respect to the stator along a second axis. An integrated motor and
20 magnetic bearing consistent with the invention is capable of providing simultaneously both
21 rotational torque and radial bearing force.

22 In method form, a method for providing integral electromagnetic motor and bearing
23 functions comprises sensing a first radial position of a rotor, the rotor comprising a plurality of

1 permanent magnets, with respect to a stator along a first axis, the stator comprising a plurality of
2 independently controlled coil segments magnetically coupled to the permanent magnets; and
3 sensing a second radial position of the rotor with respect to the stator along a second axis; and
4 delivering current to at least one coil segment, the amount of current based on at least one sensed
5 position.

6 **Brief Description of the Drawings**

7 Figure 1A depicts a conventional brushless DC motor with magnetic bearing
8 components;

9 Figure 1B depicts a conventional reluctance motor with magnetic bearing components;

10 Figure 2 depicts an integrated magnetic bearing and toothless DC brushless motor
11 according to one exemplary embodiment of the present invention;

12 Figure 2A depicts a controller for integrated magnetic bearing and motor of Figure 2;

13 Figure 3 depicts one exemplary vector relationship between force (current) direction in
14 each segment versus the resulting forces and torque of the integrated magnetic bearing and motor
15 of Figure 2;

16 Figure 4 depicts another exemplary vector relationship between force (current) direction
17 in each segment versus the resulting forces and torque of the integrated magnetic bearing and
18 motor of Figure 2;

19 Figure 5 depicts numerous possible combinations of segment current (force) and torque
20 relationships of the integrated magnetic bearing and motor of Figure 2; and

21 Figure 6 depicts an exemplary thrust bearing in an exemplary embodiment of the present
22 invention.

Detailed Description of Exemplary Embodiments

Figure 2 depicts an integrated magnetic bearing and toothless DC brushless motor 10 according to one exemplary embodiment of the present invention. In the present exemplary embodiment, the integrated motor 10 includes a generally circular stator 12 that includes a plurality of coil phases 14 arranged around the inner periphery of the stator. Depicted in Figure 2 is a plurality of coil segments, each containing coils, wherein each coil segment comprises any number of phases (at least two), and the exemplary arrangement illustrated is a three-phase arrangement, i.e., phase 1, 2 and 3. The present invention equally contemplates other phase numbers, and should be generally and broadly construed as any polyphase coil arrangement. The motor also includes a rotor 16 that has a plurality of permanent magnets 18 placed along the outer periphery of the rotor, and magnetic coupled to the coils. The magnets are magnetized in alternating north and south polarity in the radial direction. A clearance gap 24, or air gap, is provided between the rotor and the stator, which may be sized in proportion to the vibration isolation requirement (e.g., a .020" gap has been demonstrated in conjunction with an 8" diameter rotor coupled with an 11" (OD) diameter stator).

The motor 10 also includes radial position sensors 20 and 22 (not shown) disposed in or adjacent to the clearance gap 24 between the stator 12 and rotor 16. The position sensors 20 and 22 (or "gap sensors") detect the relative position of the stator with respect to the rotor along the Y-axis and X-axis, respectively. The particular position sensor utilized is not important to understanding the present invention and may comprise optical probes, and/or hysteresis probes, and/or capacitive sensors, and/or scale encoders, and/or proximity sensors, and/or other position sensors known in the art. Each position sensor generates a signal proportional to the radial

1 position of the rotor with respect to the stator along the x- and y-axes, by measuring the width of
2 the gap 24 therebetween.

3 Advantageously, the present invention logically segments the motor 10 into four separate
4 equal-length coil segments, labeled Coil Segments 1, 2, 3 and 4. In the present invention, torque
5 is applied to each of the coil segments independently (or to groups of coil segments, e.g., as in
6 three-phase motors) to achieve both a desired rotational speed (ω) and a desired radial position.
7 Figure 2A depicts a generic controller 30 that is adapted to receive rotational and radial position
8 feedback data and generate independent power signals to each of the segments of the motor.

9 Figure 2 illustrates how independent torque and bearing forces are generated using four
10 separately controlled arced segments. By controlling the current in each segment, the bearing
11 forces in both the x-direction and the y-direction can be controlled for each segment and summed
12 to get the total forces in the x- and y-direction. With position sensors and controls (not shown),
13 this will allow the system to stabilize the shaft within the radial clearance gap as well as feature
14 vibration isolation and cancellation.

15 Figure 3 illustrates the vector relationship between force (current) direction in each
16 segment versus the resulting forces and torque. In practice, the phase relationship and size of the
17 current in each phase can be of smoothly varying value; however, in this example, all forces have
18 the same absolute value of one unit. F1 and F3 cancel each other out in the x-direction and F2
19 and F4 cancel each other out in the y-direction. By adding the vectors together, it is apparent that
20 the resultant force is equal to zero. There will be no resultant force in the x- or the y-direction.
21 Each force does produce a rotational torque, however. For each segment, torque is the tangential
22 component of the force value multiplied by the radius. With a clockwise rotation assumed to be
23 in the positive direction, it can be seen that all forces in this case produce a positive torque.

1 Assuming that all the radii are the same and that all forces are tangential, the resultant torque is
2 obtained by adding the force values together and multiplying by the common radius.

3 Figure 4 also illustrates the vector relationship between force (current) direction in each
4 segment versus the resulting forces and torque. As in the previous example, all forces have the
5 same absolute value of one unit. F1 and F3 do not cancel each other out in the x-direction nor do
6 F2 and F4 cancel each other out in the y-direction. By adding the vectors together, it is apparent
7 that the resultant force is not equal to zero. There will be a resultant force in the x- and the y-
8 direction. Each force still produces a rotational torque, however. As before, in each segment,
9 torque is the tangential component of the force value multiplied by the radius. With a clockwise
10 rotation assumed to be in the positive direction, it can be seen that not all forces in this case
11 produce a positive torque. Assuming that all the radii are the same and that all forces are
12 tangential, the force values can be added together and multiplied by the common radius to get the
13 resultant torque. Adding the force values together produces a value of zero, which, multiplied by
14 the radius, produces a torque value of zero as well.

15 Figure 5 shows several other possible combinations of segment current (force) and torque
16 relationships. Note that in all cases, each "+" sign or "-" sign represents a force with a
17 magnitude of one unit or a torque with a magnitude of one unit multiplied by the radius. The sign
18 represents the direction of the force or the torque, not the value. For the examples depicted in
19 Figures 3-5, it is understood that the controller of Figure 2A is adapted with an appropriate
20 control algorithm to achieve desired radial positioning of the rotor with respect to the stator.

21 Thus, it is evident that an integrated magnetic bearing and motor have been provided.
22 Those skilled in the art will recognize numerous modifications to the present invention. For
23 example, the motor 10 of Figure 2 is logically segmented into four separate segments as

1 depicted. The present invention can be adapted to any number of segments (e.g., 3 or more). Of
2 course, increasing the number of segments will increase rotational and positioning smoothness
3 and may reduce any cross-coupling effects, but may require more complicated control
4 algorithms. Additional radial position sensors may further be added, as necessary. Those skilled
5 in the art should recognize that the rotor may be configured outside the stator. Thus, the present
6 invention is equally adaptable to such configurations. It should further be noted that, in the
7 exemplary embodiment depicted in Figure 2, those skilled in the art will recognize that, since
8 this example comprises four coil segments having equal radial length, and the bearing may still
9 be levitated with only three coils, a fourth set (as illustrated and described herein) serves to
10 provide an additional degree of fault tolerance (i.e., if one coil fails, the three others are sufficient
11 to levitate the bearing). It is contemplated that other numbers of coils may be provided in
12 various configurations, and that appropriate sensing and control means are provided in any fault
13 tolerance configuration.

14 Still other modifications are possible. For example, the bearing arrangement depicted in
15 Figure 2 may be disposed on either end of a shaft (not shown) and utilized to control pointing of
16 the rotor. In this example, the rotor/stator are embedded into tubular members where each end is
17 independently controlled to position the rotor in a desired skew with respect to the stator.
18 Further, for applications comprising an off-center load, off-axis operation or run-out cancellation
19 may be provided to allow the load to be balanced, i.e., the center line of the rotor can follow a
20 circle as it rotates to center a load on top of the bearing.

21 As illustrated in Figure 6, other embodiments might comprise the use of a magnetic thrust
22 bearing 40 (e.g., a Maxwell bearing) along the shaft 50 to produce force in the axial direction, z,
23 and to stabilize the bearing. The thrust bearing and the associated thrust position (or gap)

1 sensors may be incorporated into a motor and magnetic bearing consistent with the invention, or
2 may be attached to such a motor and magnetic bearing. It should also be recognized that
3 assembly of a magnetic bearing results in attraction of the rotor to the stator (which is commonly
4 alleviated using tooling, e.g. lamination materials on the outside of the bearing), and that the flux
5 attraction indicative of this feature will provide a degree of axial thrust that may be sufficient, in
6 certain applications, to eliminate the use of a thrust bearing (e.g., the system would act as though
7 supported by one or more springs).

8 Those skilled in the art should recognize that in brushless DC motors, a commutation
9 device is required to cause the motor phase currents to be switched appropriately. Three-phase
10 systems using commutation devices comprising Hall effect transistors typically have six "states"
11 in the cycle, and may be the least expensive solution. In a magnetic bearing, however, more
12 effective means of commutating, (e.g., an encoder) are typically used. An encoder can be used
13 as a position sensor, wherein its output provides the phase position. Yet another alternative is
14 sensorless commutation, wherein voltages generated in the device at the windings are measured
15 (e.g., in the brief period during which a control stops driving the current into a coil) and
16 appropriate electronics may be provided to calculate a sensed position based on currents
17 generated in the coils.

18 Although the present invention has been described with reference to a rotary design
19 integrated magnetic bearing, the present invention applies equally to linear motor designs. For
20 example, the motor 10 of Figure 2 can easily be formed into a linear design by "unrolling" the
21 stator and rotor. The segmented coil design described herein would apply to such a linear
22 design. These and other examples and modifications will become apparent to those skilled in the

1 art, and all such examples and modifications are deemed within the scope of the present
2 invention, as defined by the appended claims.

2 invention, as defined by the appended claims.

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4 We claim:

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NUMBER	NAME	STREET	CITY	STATE	ZIP
1	WILLIAM	1234	NEW YORK	NY	10001
2	JAMES	5678	LOS ANGELES	CA	90001
3	MARY	9012	CHICAGO	IL	60601
4	JOHN	3456	HOUSTON	TX	77001
5	SARAH	7890	PHOENIX	AZ	85001
6	DAVID	2345	ATLANTA	GA	30301
7	LUCAS	6789	DALLAS	TX	75201
8	EMILY	0123	SEATTLE	WA	98101
9	MICHAEL	4567	PORTLAND	OR	97201
10	AMANDA	8901	MINNEAPOLIS	MN	55401
11	CHRISTOPHER	1357	INDIANAPOLIS	IN	46201
12	STEPHANIE	2468	COLUMBIA	SC	29201
13	NATHAN	3579	MEMPHIS	TN	38101
14	KATHERINE	4680	DETROIT	MI	48201
15	BENJAMIN	5791	PHILADELPHIA	PA	19101
16	OLIVIA	6802	BOSTON	MA	02101
17	ISAAC	7913	WASHINGTON	DC	20001
18	CHARLOTTE	8024	NEW ORLEANS	LA	70101
19	LEONARD	9135	SAO PAULO	SP	05001
20	HANNAH	0246	RIO DE JANEIRO	RJ	20001
21	ISAAC	1357	SAO PAULO	SP	05001
22	CHARLOTTE	2468	SAO PAULO	SP	05001
23	LEONARD	3579	SAO PAULO	SP	05001
24	HANNAH	4680	SAO PAULO	SP	05001
25	ISAAC	5791	SAO PAULO	SP	05001
26	CHARLOTTE	6802	SAO PAULO	SP	05001
27	LEONARD	7913	SAO PAULO	SP	05001
28	HANNAH	8024	SAO PAULO	SP	05001
29	ISAAC	9135	SAO PAULO	SP	05001
30	CHARLOTTE	0246	SAO PAULO	SP	05001